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FIELD CALIBRATION OF THE RS-14 DUAL-CHANNEL AIRBORNE INFRARED IMAGER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

The collection of data on the NASA Earth Resources Aircraft Program Mission 98 (Puerto Rico and Barbados) presented an opportunity to compare the output of the Barnes PRT-5 Precision Radiation Thermometer and the RS-14 Dual-Channel Airborne Infrared Imaging System aboard the NASA NP3A aircraft. The RS-14 as flown on Mission 98 was not a fully calibrated system. Inspection of the RS-14 output and comparison of the RS-14 data with the PRT-5 data suggest a simple calibration procedure for the RS-14. This calibration procedure indicates that very little error is introduced in the thermal channel because of the use of different parts of the optics during a scan and that the measured case temperature apparently is not a representative cavity temperature for the system.

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SUMMARY

The collection of data on the NASA Earth Resources Aircraft Program Mission 98 (Puerto Rico and Barbados) presented an opportunity to compare the output of the Barnes PRT-5 Precision Radiation Thermometer and the RS-14 Dual-Channel Airborne Infrared Imaging System aboard the NASA NP3A aircraft. The RS-14 as flown on Mission 98 was not a fully calibrated system in that (1) the effects of the IRTRAN-2 windows between the internal calibration sources and the sensor were not known, (2) the effects of using different parts of the optics in a scan were not known, and (3) the representativeness of the measured cavity temperature was not known. The PRT-5 is a calibrated system; however, it is much less sensitive than the RS-14. Inspection of the RS-14 output and comparison of the RS-14 data with the PRT-5 data suggest a simple calibration procedure for the RS-14. The RS-14 data corrected by this procedure and integrated over the field of view of the PRT-5 agree with the PRT-5 measured radiation temperature within 0.5° C. This calibration procedure also indicates that very little error is introduced in the thermal channel (channel 2) because of the use of different parts of the optics during a scan and that the measured case temperature apparently is not a representative cavity temperature for the system.

INTRODUCTION

Mission 98 of the NASA Earth Resources Aircraft Program consisted of flights over and in the vicinity of Puerto Rico and Barbados during the last part of June 1969. Scheduling requirements did not allow time for an adequate laboratory calibration of the new RS-14 system before this mission. However, the applicability of a laboratory calibration to Mission 98 would have been questionable even if one had been performed because of possible contamination of the system by hydraulic fluid while the aircraft was in Puerto Rico.

Inspection of the data collected by the RS-14 and the PRT-5 during Mission 98 suggests a simple method of calibration of the RS-14 that permits retrieval of quantitative data taken with the system before laboratory calibration. This calibration also should be useful as a field check on the stability of laboratory calibration on future missions.

The data used to determine the calibration were collected on the ramp at Seawell Airport, Barbados, before Flight 7 of Mission 98 on June 27, 1969. The calibration was tested by comparing the output of the two systems at three points during Run 2 of Line 2 of Flight 7 from an altitude of 3000 feet above the surface.

DESCRIPTION OF RS-14 AND PRT-5 SYSTEMS

Dual-Channel Airborne Infrared Imaging System

The RS-14 (manufactured by Texas Instruments, Inc., Dallas, Texas) is a passive roll-stabilized system that scans the ground area normal to the aircraft flight path at the rate of 66.7 scans/sec (3-milliradian instantaneous field of view) or 200 scans/sec (1-milliradian instantaneous field of view), with a lateral coverage of 40° on either side of the nadir. Channel 1 contains two indium/antimonide infrared detectors cooled to ≤26° K that detect energy in the 3- to 5-micron range. In the future, channel 1 will be capable of adaptation to the use of photomultiplier tubes to detect energy in the ultraviolet and visible portions of the spectrum. Channel 2 contains two mercury-doped germanium infrared detectors cooled to ≤26° K that detect energy in the 8- to 14-micron range (the thermal band). The manufacturer's claimed noise-equivalent temperature for the RS-14 system in the slow-scan-rate mode used for Mission 98 is 0.3° C.

The system was designed to be used as a calibrated system; that is, a given radiation temperature could be assigned a given output voltage. Two calibrated potentiometers control the temperature of the two internal calibration sources (for the infrared measurements). To ensure stable calibration temperatures, windows of IRTRAN-2 material were placed between the calibration sources and the environment. The presence of these windows, however, makes calibration of the system more difficult and more subject to change with time. The windows not only attenuate the radiation emitted by the internal calibration sources but also emit radiation themselves and, most importantly, reflect the radiation emitted by the cavity containing the optics and the sensors. Laboratory calibration of the system can account for these effects on future missions. However, changes in window transmissivity and reflectivity caused by the deposition of dust, salt, or other contaminants on the window may require frequent recalibration.

Precision Radiation Thermometer

The Barnes PRT-5 has a 2° field of view. The detector is an immersed thermistor bolometer. The absolute system accuracy of ±0.5° C (claimed) is achieved by controlling the temperature of a heated in-line reference cavity within the optical head of the PRT-5. Incoming target radiation (8 to 14 microns) is compared continuously with the known radiation of the internal reference. The difference is converted into a proportional electrical signal that is equivalent to the target radiation temperature. The output of the PRT-5 is proportional to the fourth power of the absolute radiation temperature; thus, a correction should be made to any linear interpolation between the high and low range marks. On Mission 98, the PRT-5 aboard the aircraft was compared with another radiation thermometer owned by the Barnes Company. Agreement between the two units was within 0.5° C.

GRAY WINDOW FIELD CALIBRATION OF THE RS-14

The following discussion of the RS-14 is concerned mainly with the thermal channel (channel 2, 8 to 14 microns) because it is the channel that corresponds to the PRT-5 data. Channel 1, which is almost equally sensitive to reflected solar radiation and to thermal radiation, is mentioned, however. The film output of the RS-14 is not used; instead, the taped data from which quantitative values can be determined are used. The photographs used are from the KA-62 cameras. The calibration steps are as follows.

The effects of the window between the internal calibration sources and the detector are considered first. As the detector "looks" at the calibration sources, the energy it receives can be expressed as the sum of (1) the energy emitted by the calibration source, which passes through the window, (2) the energy emitted by the window, and (3) the energy emitted by the cavity (which contains the detector) and reflected from the window to the detector. Assuming that the window emits energy at the temperature of the cavity or does not emit energy itself but merely transmits and reflects, the effective temperature as the detector looks at the calibration source is then

$$T_{eff} = \left[(\tau)T_{cal}^4 + (1 - \tau)T_{cavity}^4\right]^{1/4} \tag{1}$$

where T_{eff} is the effective blackbody absolute temperature, τ is the transmissivity of the window, T_{cal} is the absolute blackbody temperature of the source, and T_{cavity} is the effective absolute blackbody temperature of the cavity (cavity temperature)[1]. Thus, the effective blackbody temperature changes from T_{cal} where $\tau = 1.0$ to approximately one-half $(T_{cal} + T_{cavity})$ where $\tau = 0.5$. This effect is shown in figure 1, where the solid curves show the change in the effective high and low internal-calibration temperatures for preflight calibration as a function of transmissivity of the windows, assuming that the measured case temperature is representative of the cavity temperature. The dashed curves in figure 1 are drawn for a representative cavity temperature that is 5.9° C cooler than the case temperature measured. The choice of this value will be discussed later. Figure 1 shows that the range in effective temperature between high and low calibration decreases with a decrease in the window transmissivity for the cavity temperature given.

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[1]It should be noted that the cavity temperature represents the integrated effect of emissions from the cavity containing the detector, which are reflected from the window in front of the calibration source into the detector. This temperature is dependent not only on the emissivities and temperatures within the detector but also upon the geometry of the cavity with respect to the detector. This temperature may, and in this instance does, differ from the temperatures of the case (measured at one point in the cavity).

Figure 2 is a similar diagram except that the case temperature is the temperature observed during data collection. The frequency dependency of the IRTRAN-2 window material is shown in figure 3. Note that the window transmissivity varies irregularly between 8 and 14 microns. Figure 3 is included only for interest; no part of the calibration described in this report makes use of this information. Calibration may be performed by using curves of this sort; however, curves for each part of the internal optics and for sensor sensitivity and knowledge of the "seeing" factors would also be required.

The next step in the calibration requires the use of preflight data. Before starting the aircraft, the ramp surface equivalent blackbody temperature (ramp temperature) was measured at 30.7° C by the PRT-5 and a blackbody (of questionable nature) was measured at 40.8° C. The view as seen by the RS-14 (channel 2) at the time of these measurements is shown in figure 4. Note these values in relation to the high and low internal-calibration values.

Using the preflight temperatures of the ramp and the blackbody, a curve fit that related the temperature to the RS-14 output was performed in the following manner. Constants C and B were determined from equations (2) and (3).

$$T_{ramp} + 273.2^\circ \text{ C} = \left(C + BY_{ramp}\right)^{1/4} \tag{2}$$

$$T_b + 273.2^\circ \text{ C} = \left(C + BY_b\right)^{1/4} \tag{3}$$

where T is the temperature in degrees Celsius as observed by the PRT-5 and Y is the value (in strip-chart increments from low calibration) of the RS-14 output. Using these values of B and C, the curve relating temperature to RS-14 output was drawn. The effective high and low calibration temperatures were thus determined (fig. 5). The difference between the high and low calibration temperature was 11.4° C.

In figure 1, a difference between the high and low calibration temperatures of 11.4° C is found to occur with an effective window transmissivity of 0.54. Both the high and low calibration temperatures are too high, however, if the effective cavity temperature is assumed to be the measured case temperature. The high and low calibration temperatures are correct for an effective cavity temperature that is 5.9° C cooler than the measured case temperature. This cooler effective temperature is not unreasonable if one considers that the window views the cooled detector as well as the case.

The high and low calibration temperatures for data collection are defined and noted in figure 2, where it is assumed that the difference between the measured case temperature and the effective cavity temperature remains unchanged between preflight calibration and data collection.

With known effective high and low calibration temperatures, the RS-14 channel 2 output is quantitative data. Using this information, the radiation temperature observed over the water on Line 2 of Flight 7 of Mission 98 was determined to be 24.9° C. The PRT-5 indicated a temperature of 25.0° C (fig. 6). In figure 6, the RS-14 channel 2 output does not appear to be affected seriously by the scan angle, implying that the use of different parts of the optics during a scan is not a serious problem. Note also the hump in the middle of the channel 1 scan that is caused by sunglint.

The actual water temperature was probably much nearer the 28.4° C measured over the Barbados Oceanographic and Meteorological Experiment (BOMEX) array earlier in the month. The difference between the observed and the real temperatures is due primarily to the effects of the intervening atmosphere (surface to 3000 feet). The important point is agreement between the systems.

An inland scan on the same run is shown in figure 7. The RS-14 output shows the observed (from 3000 feet) radiation temperatures of individual trees, roads, and fields. By integrating the RS-14 output spatially over the field of view of the PRT-5, the RS-14 temperature is 33.5° C and the PRT-5 indicates a temperature of 34° C. A scan taken a short time later is shown in figure 8; the RS-14 and PRT-5 data both indicate a radiation temperature of 33.5° C.

To arrive at this agreement, it was necessary to correct both the PRT-5 and RS-14 output for linear interpolation. The correction for the RS-14 is not large because of the proximity of the low and high calibration temperatures. For the PRT-5, however, the correction can be as large as 2° C (fig. 9). Many errors can be introduced in the use of dividers to obtain data from the strip charts. These errors may have aided the agreement between the two systems. However, the RS-14 output as calibrated by the procedure described herein is apparently well within the range of accuracy acceptable to many users. Certainly, the error is less than the error introduced by the atmosphere.

A worksheet to aid in field calibration of the RS-14 is given in the appendix.

CONCLUSIONS AND RECOMMENDATIONS

1. The RS-14 is an operational scanner capable of providing quantitative data with acceptable accuracy when used in the proper manner.

2. Although not as accurate as a laboratory calibration, the type of calibration described herein has the following definite advantages.

a. The calibration can be done easily without removal of the system from the aircraft.

b. The calibration can correct for what otherwise would be a "field foulup." For example, on Mission 98, both the PRT-5 and the RS-14 were covered with hydraulic fluid while the aircraft was in Puerto Rico. This calibration technique accounts for the possible effects of the fluid; the use of laboratory calibration charts would not.

3. The effect of using different parts of the optics as the scan angle changes apparently is small enough to be of little concern. Future laboratory tests will be made on this effect.

It is recommended that all flights using scanners be made with the PRT-5 or Block Radiometer and that a preflight calibration be made of both the scanner and the radiometer.

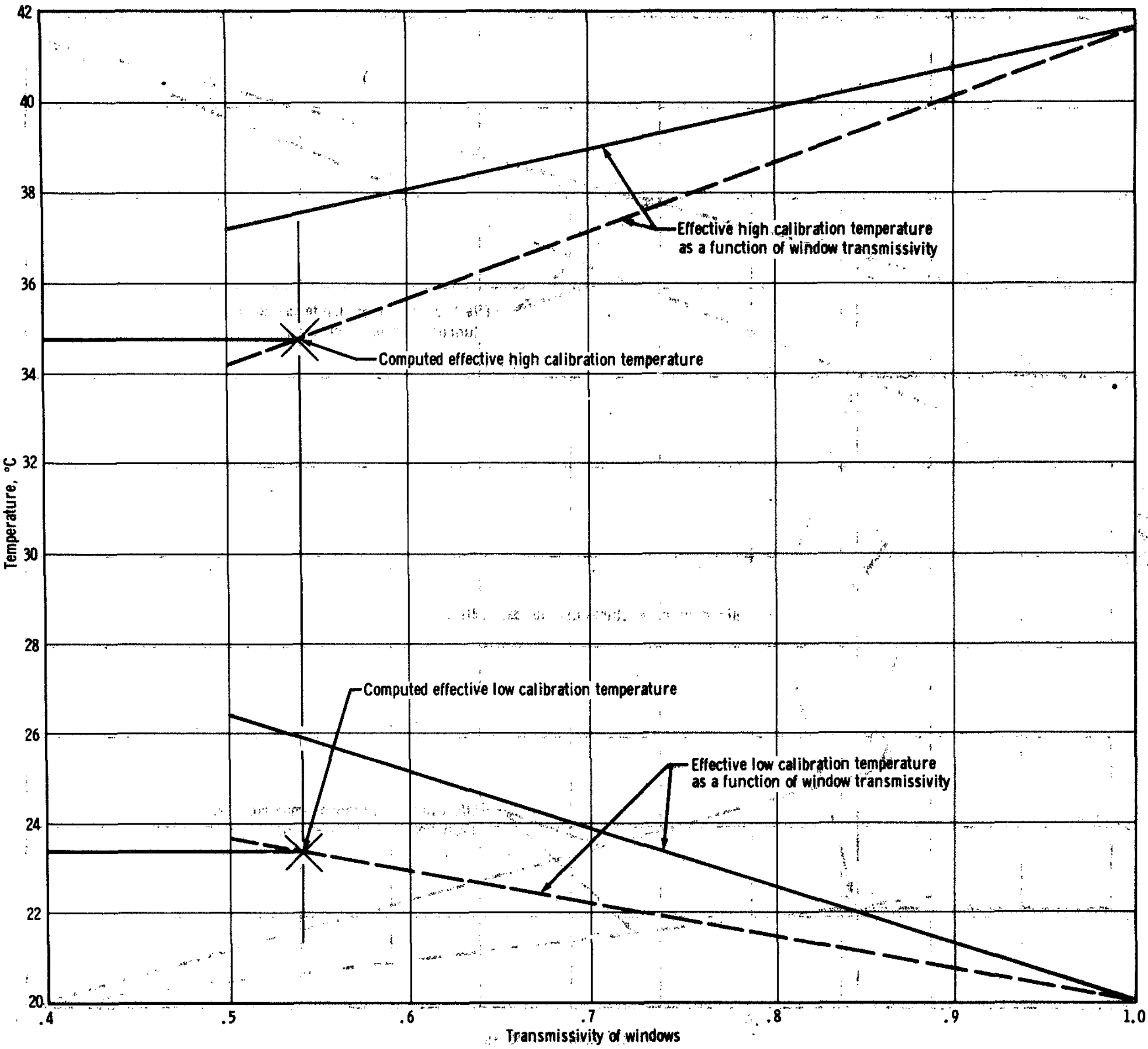

Figure 1.- Effective calibration temperatures for a high-calibration temperature of 41.5° C, a low calibration temperature of 20.0° C, and a case temperature of 32.5° C, assuming that the window and case are at the same temperature and neglecting the variation in transmissivity with wavelength (ground calibration at Barbados). The dashed curves are for an effective case temperature 5.9° C cooler than measured.

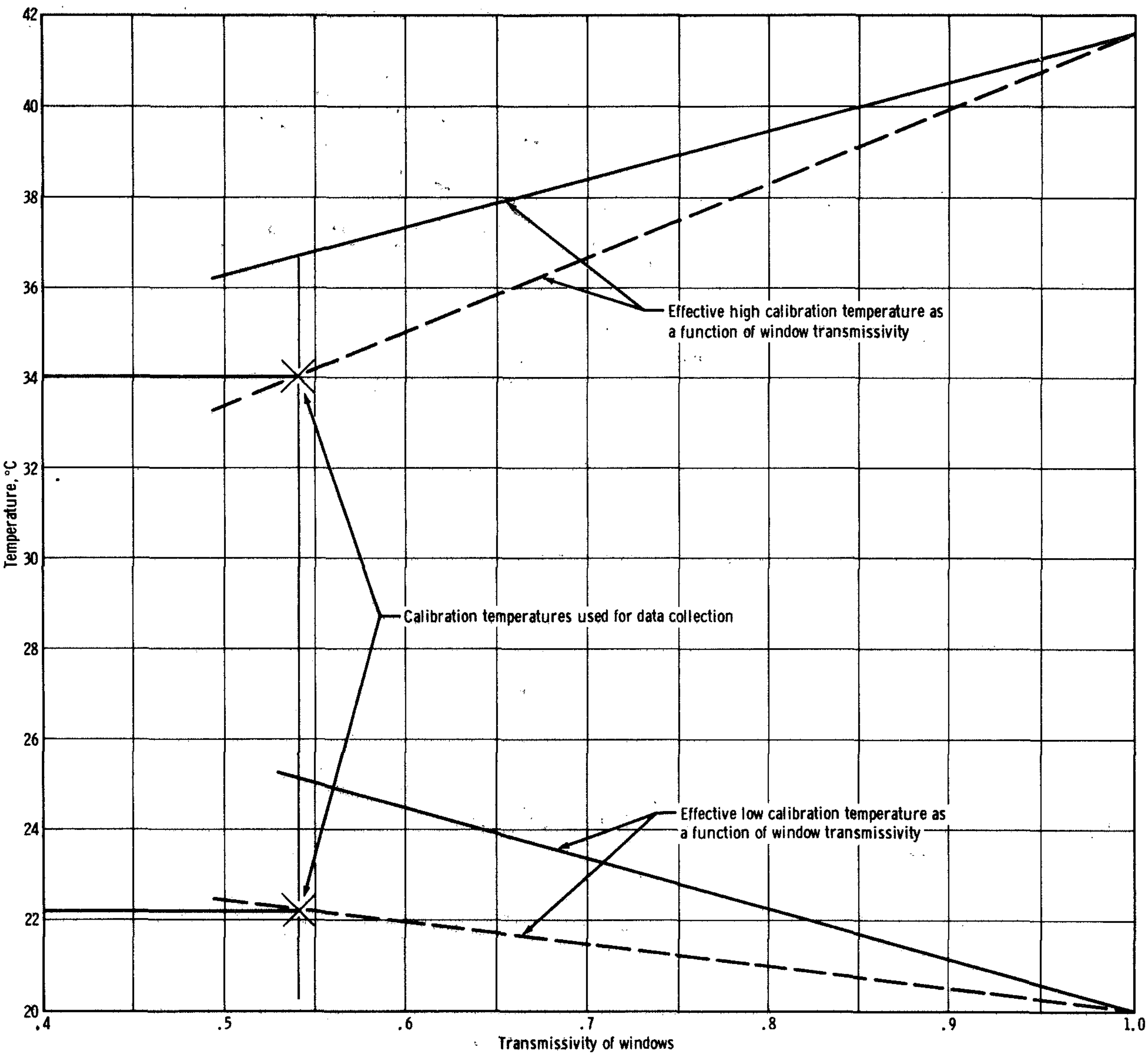

Figure 2. - Effective calibration temperatures for a high calibration temperature of 41.5° C, a low calibration temperature of 20.0° C, and a case temperature of 30.9° C, assuming that the window and case are at the same temperature and neglecting the variation in transmissivity with wavelength (flight data). The dashed curves are for an effective case temperature 5.9° C cooler than measured.

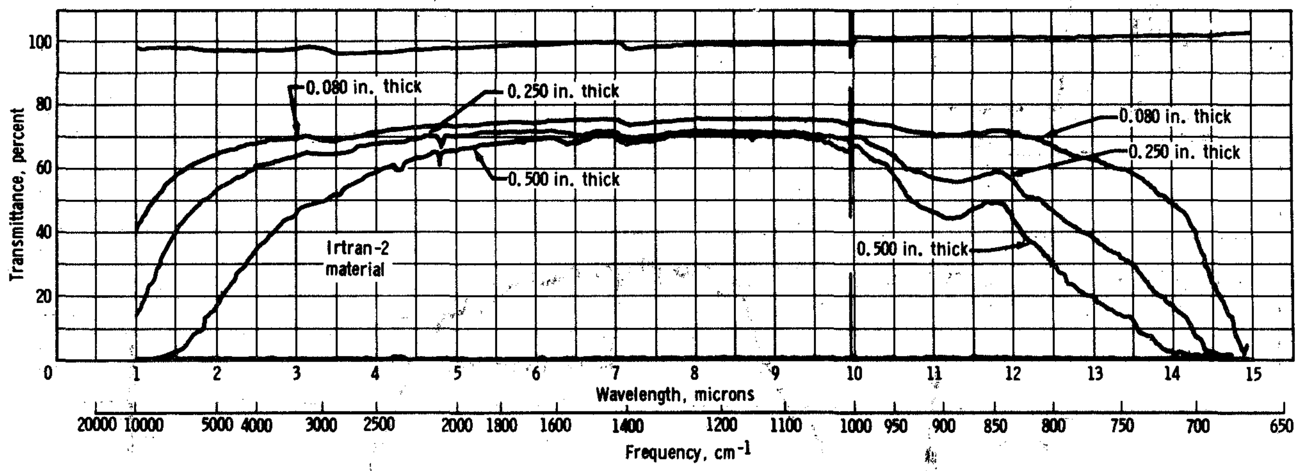

Figure 3. - Transmissivity of window material as a function of wavelength (window thickness is 0.040 inch).

Figure 4. - Ramp and blackbody as seen by the RS-14. The temperature values are as determined by the PRT-5.

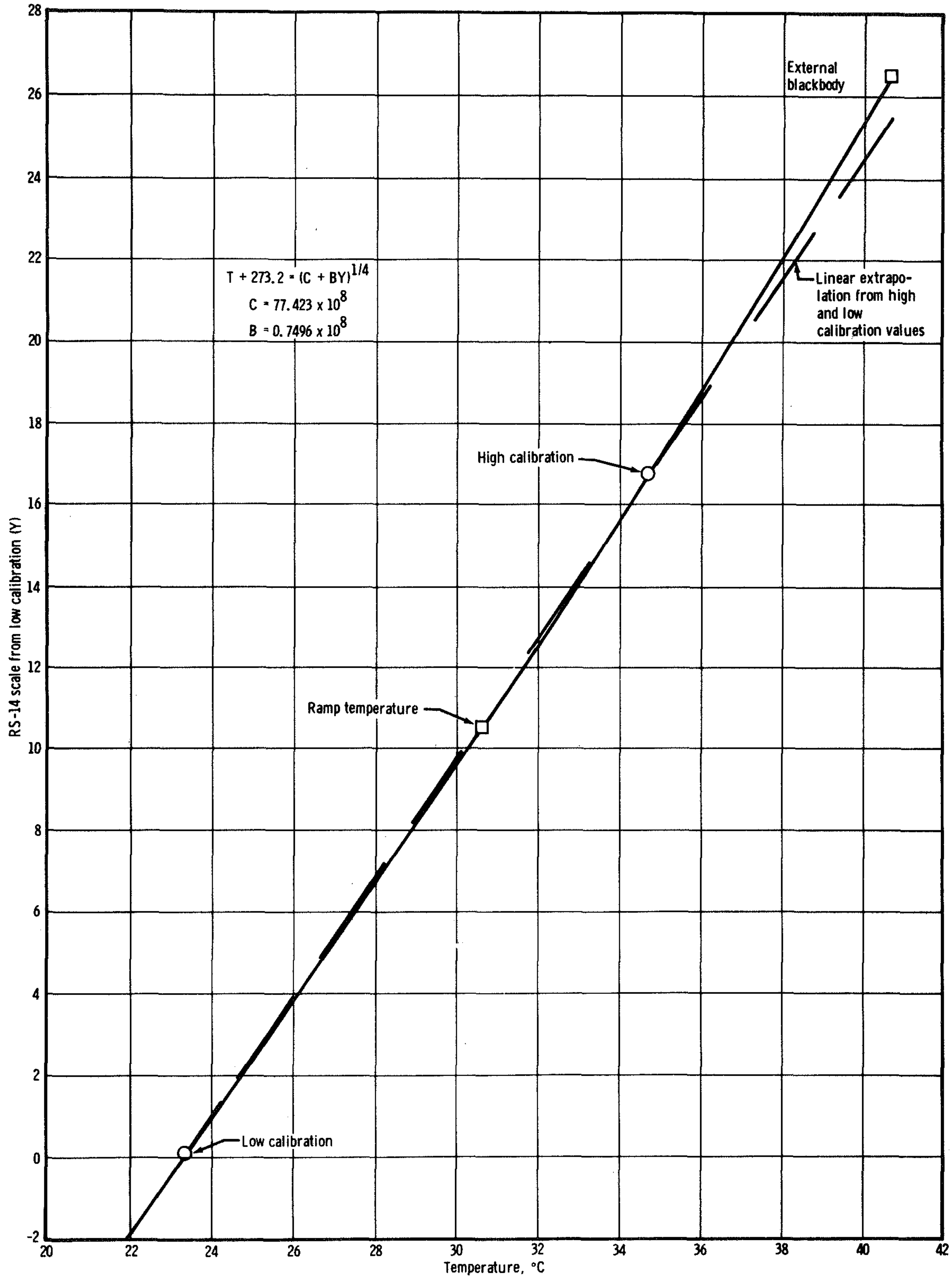

Figure 5. - Curve fitted to ramp and blackbody temperatures to determine the effective internal calibration temperatures of the RS-14.

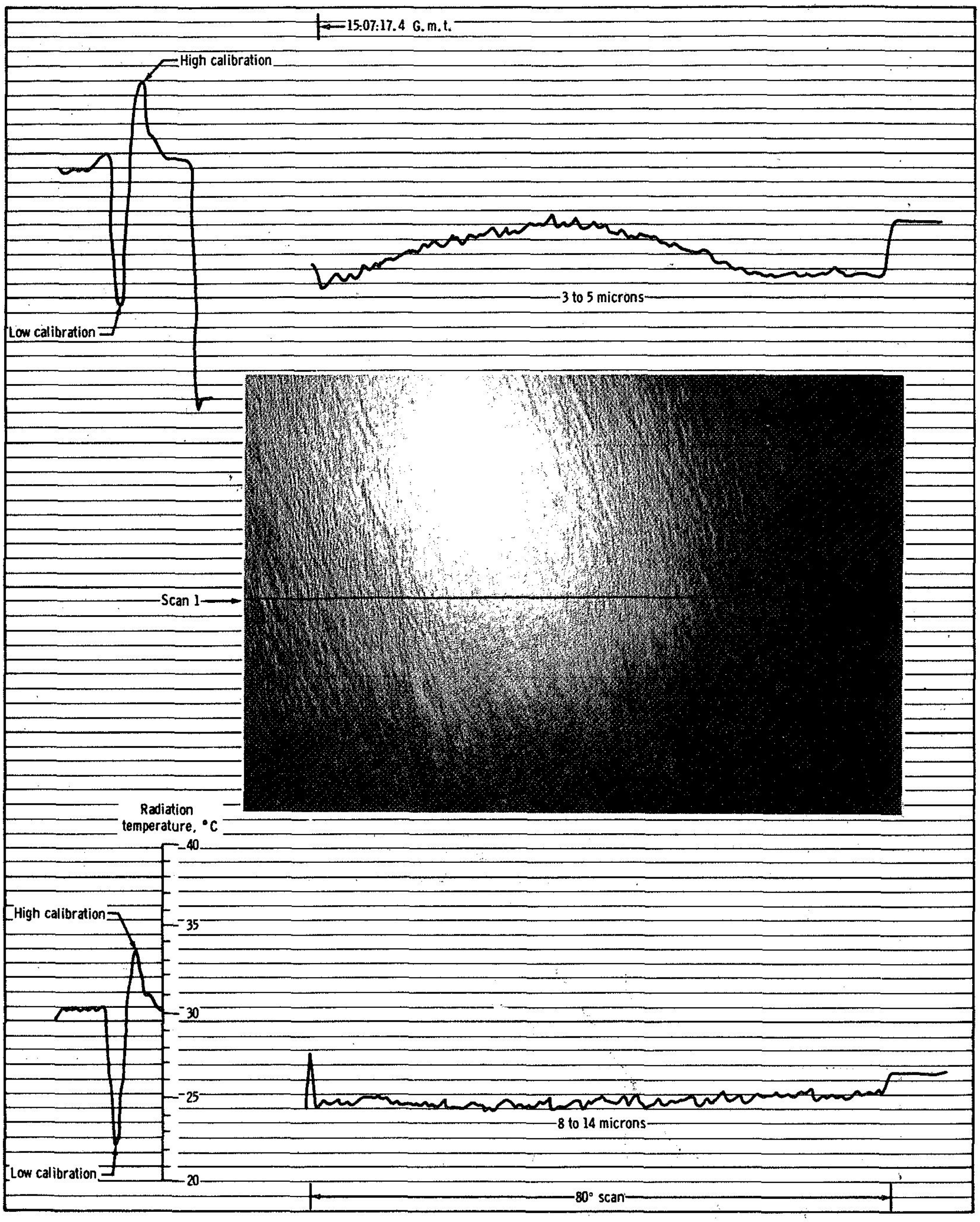

Figure 6. - Scan 1 of the RS-14; channel 1 (3 to 5 microns, top) and channel 2 (8 to 14 microns, bottom).

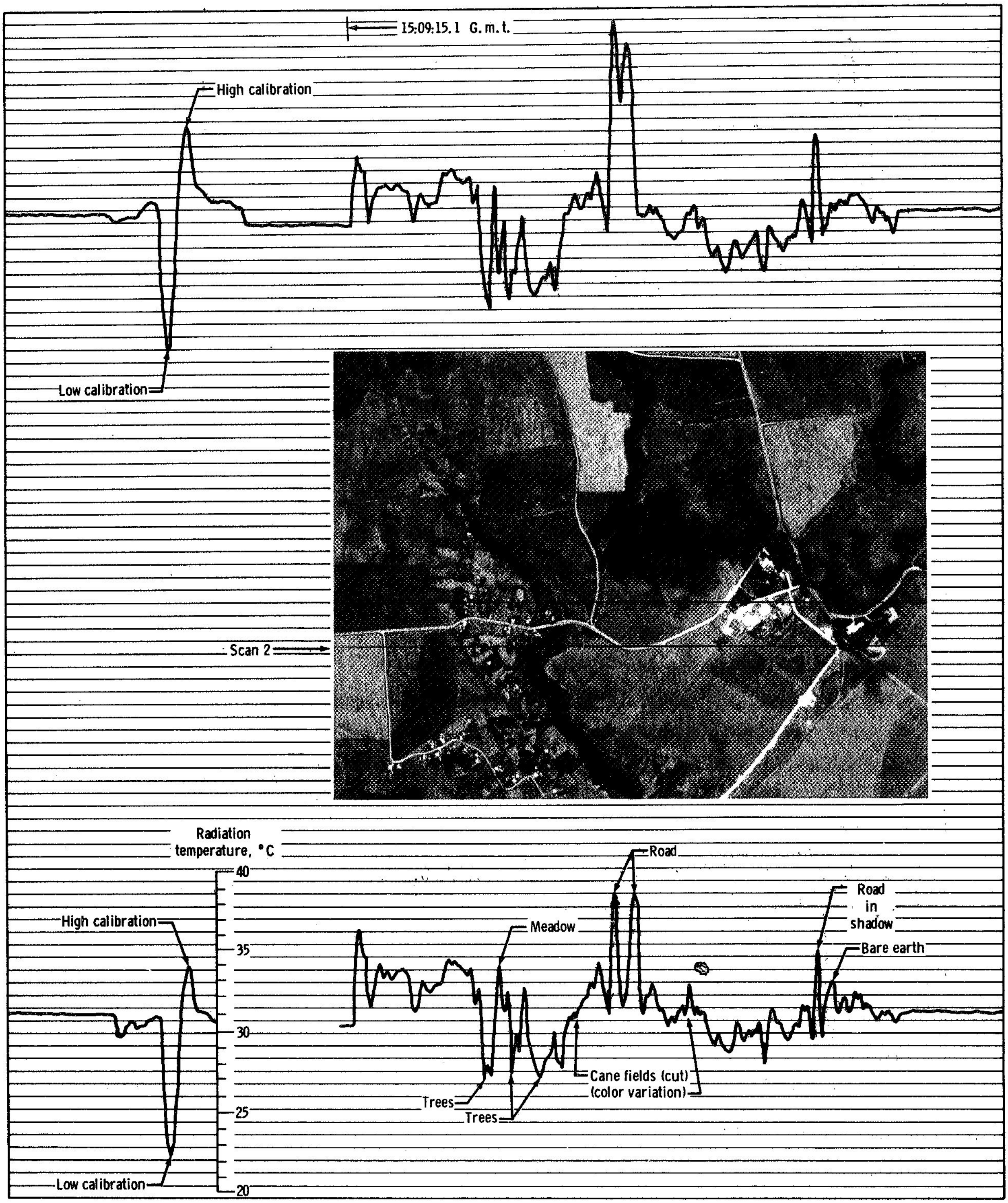

Figure 7. - Scan 2 of the RS-14; channel 1 (3 to 5 microns, top) and channel 2 (8 to 14 microns, bottom).

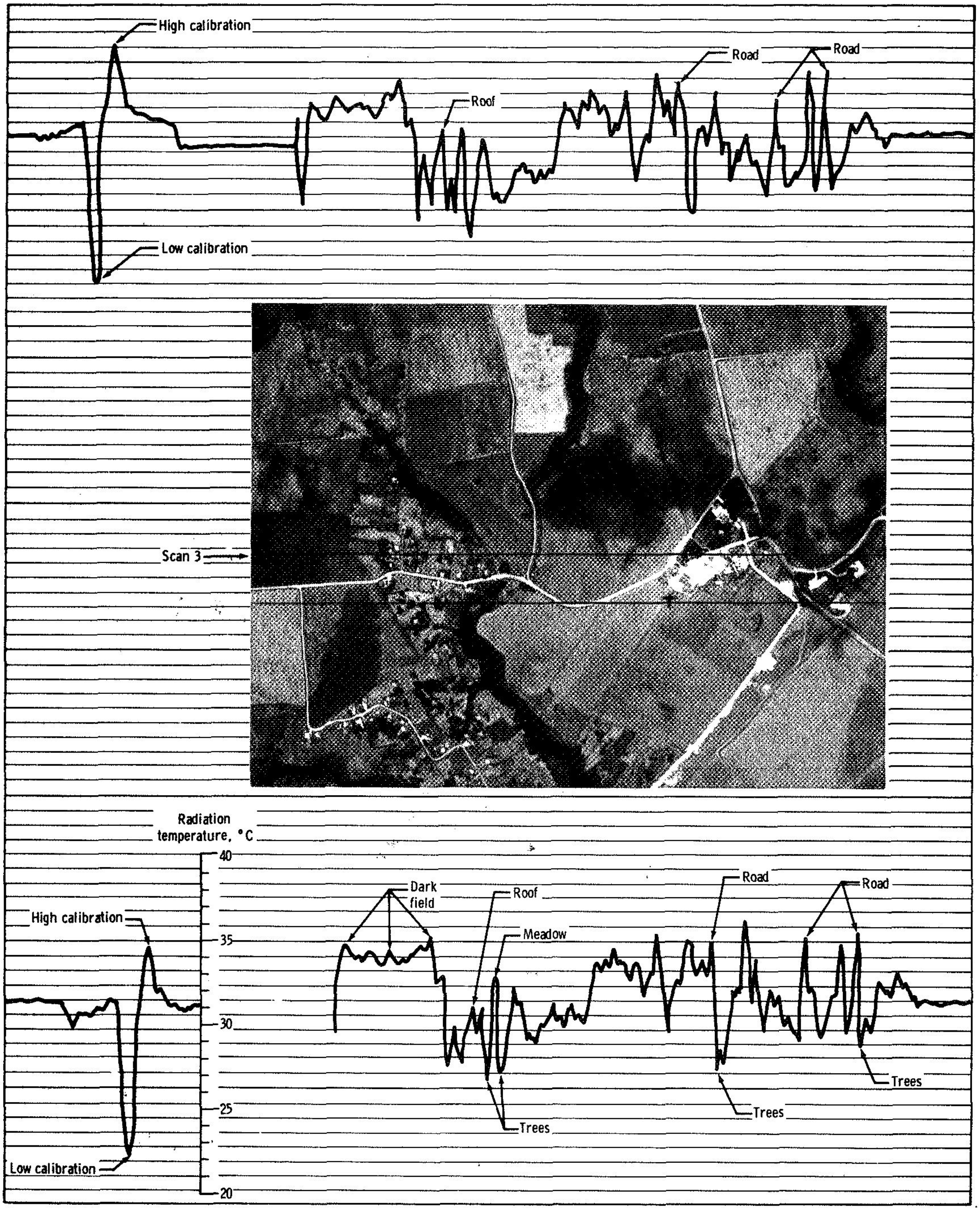

Figure 8. - Scan 3 of the RS-14; channel 1 (3 to 5 microns, top) and channel 2 (8 to 14 microns, bottom).

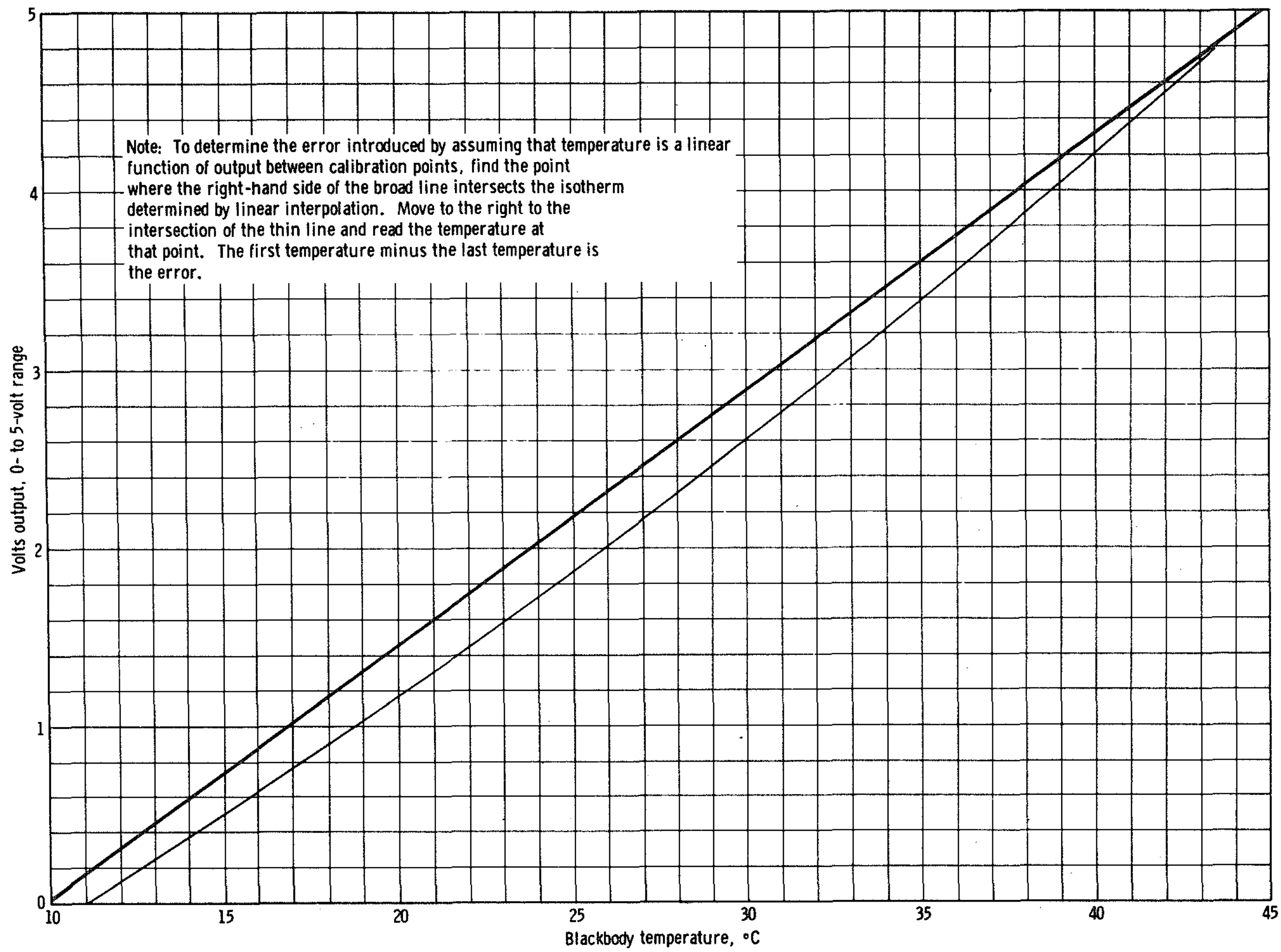

Figure 9. - Calibration curve for the PRT-5.

APPENDIX

WORKSHEET FOR FIELD CALIBRATION OF THE RS-14

To field calibrate the RS-14 by using the PRT-5 or Block-Radiometer data, the following observations must be made.

1. On the ground:

Potentiometer setting for high internal-calibration source	_____ volts = _____ °C
Potentiometer setting for low internal-calibration source	_____ volts = _____ °C
Case temperature of the RS-14	_____ volts = _____ °C
Ramp temperature measured by PRT-5 or Block Radiometer	_____ °C
Blackbody temperature measured by PRT-5 or Block Radiometer	_____ °C
*RS-14 output over ramp	________ relative units
*RS-14 output over blackbody	________ relative units
*RS-14 output for high calibration	________ relative units

*NOTE: If the calibration is to be done on a real-time basis, the grid on the RS-14 scope should be used, setting the low calibration reading to zero. If the calibration is to be done after the flight, these data do not have to be recorded. It is necessary to record the time when the RS-14 views the ramp and blackbody; a marking signal should be put on the tape by the operator.

2. On the data-collection run:

Potentiometer setting for high internal-calibration source	_____ volts = _____ °C
Potentiometer setting for low internal-calibration source	_____ volts = _____ °C
Case temperature of the RS-14	_____ volts = _____ °C

A detailed description of the calibration procedure follows.

1. Bring the RS-14 or PRT-5 or Block Radiometer to operating condition.

2. Take the necessary steps to ensure that the area under the aircraft that is observed by the PRT-5 is similar to that observed by the RS-14. Be particularly cautious of cracks in the pavement, oil spots, and differences in the degree of shadow.

3. From the potentiometer setting, determine the temperature of the high internal-calibration source. Plot this temperature on line A in figure 10. $T_1 =$ ______ °C

4. From the potentiometer setting, determine the temperature of the low-calibration source. Plot this temperature on line A in figure 10. $T_2 =$ ______ °C

5. Determine the measured case temperature of the RS-14. Plot this temperature on line B in figure 10. $T_3 =$ ______ °C

6. Draw a straight line from T_1 to T_3 in figure 10. Label the line "High calibration." Draw a straight line from T_2 to T_3 and label it "Low calibration."

7. Using the increments on the RS-14 scope (for real-time calibration) or on the strip chart (for postflight calibration), establish a scale of arbitrary units of the RS-14 output. For convenience, set the low calibration value equal to zero.

8. Determine the ramp temperature as indicated by the PRT-5 or Block Radiometer. $T_4 =$ ______ °C

9. Determine the output of the RS-14 in arbitrary units as the RS-14 views the ramp. $Y_1 =$ ______

10. Determine the blackbody temperature as indicated by the PRT-5 or Block Radiometer. $T_5 =$ ______ °C

11. Determine the output of the RS-14 in arbitrary units as the RS-14 views the blackbody. $Y_2 =$ ______

12. Determine $\dfrac{\left(T_4 + 273.2\right)^4 - \left(T_5 + 273.2\right)^4}{Y_1 - Y_2} = B.$ $B =$ ______

13. Determine $(T_4 + 273.2)^4 - BY_1 = C$. $C =$ ______

14. Determine the RS-14 output in arbitrary units for high internal calibration. $Y_3 =$ ______

15. Determine the equivalent high-calibration temperature $(C + BY_3)^{1/4} - 273.2 = T_6$. $T_6 =$ ______ °C

16. Determine the RS-14 output in arbitrary units for low internal calibration. $Y_4 =$ ______

17. Determine the equivalent low-calibration temperature $(C + BY_4)^{1/4} - 273.2 = T_7$. $T_7 =$ ______ °C

18. Locate the value of transmissivity on figure 10 where the difference between the high and low calibration lines equal $(T_6 - T_7)$. Draw a vertical line along this value of transmissivity and label the line "line C."

19. Plot T_6 and T_7 on line C.

20. Draw a straight line from T_1 through T_6 to line B.

21. Draw a straight line from T_2 through T_7 to line B. The lines should intersect on line B at a common point, which is the effective case temperature. $T_8 =$ ______

22. Determine the difference between the measured case temperature and the effective case temperature. $(T_3 - T_8) = \Delta T =$ ___ °C

23. Determine the measured case temperature at the time of data collection. $T_9 =$ ______ °C

24. Determine $T_9 - \Delta T$ at the time of data collection. $T_{10} =$ ______ °C

25. From the potentiometer setting, determine the temperature of the high internal-calibration source at the time of data collection. $T_{11} =$ ______ °C

26. From the potentiometer setting, determine the temperature of the low internal-calibration source at the time of data collection.

T_{12} = ____________ °C

27. In figure 10, the point where a line drawn from T_{10} to T_{11} intersects line C is the value of the effective high internal-calibration temperature for the collected data.

____

28. In figure 10, the point where a line drawn from T_{10} to T_{12} intersects line C is the value of the effective low internal-calibration temperature for the collected data.

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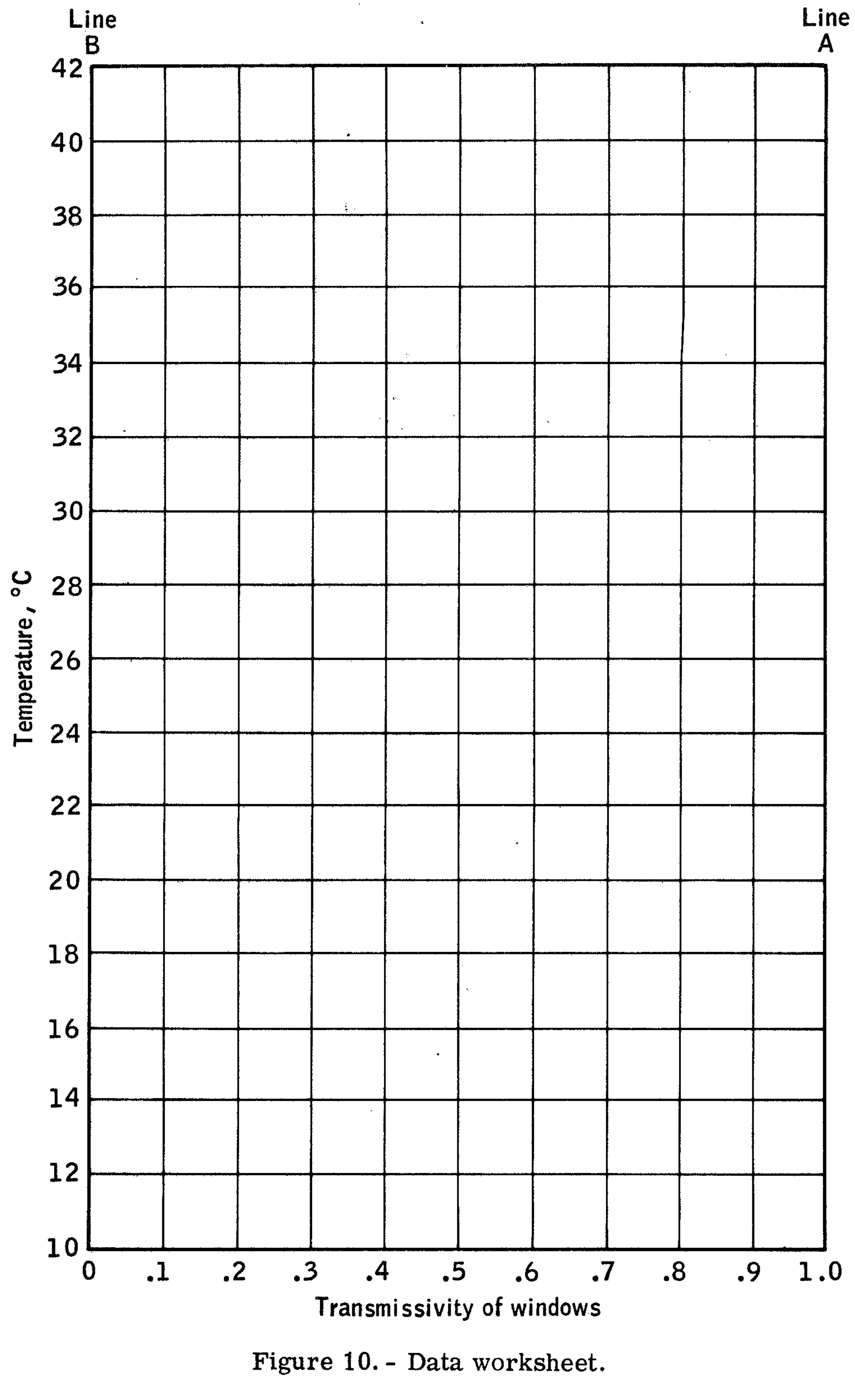

Figure 10. - Data worksheet.

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